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Understanding the variability of wind power costs

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A B S T R A C T

Wind power has a significant contribution to make in efforts to abate CO_2 emissions from global energy systems. Currently, wind power generation costs are approaching parity with costs attributed to conventional, carbon-based sources of energy but the economic advantage still rests decidedly with conventional sources. Therefore, there is an imperative to ensure that wind power projects are developed in the most economically optimal fashion. For wind power project developers, shaving a few tenths of a cent off of the kilowatts per hour cost of wind power can mean the difference between a commercially viable project and a non-starter. For civic authorities who are responsible for managing municipally supported wind power projects, optimizing the economics of such projects can attenuate stakeholder opposition. This paper attempts to contribute to a better understanding of how to economically optimise wind power projects by conflating research from the fields of energy economics, wind power engineering, aerodynamics, geography and climate science to identify critical factors that influence the economic optimization of wind power projects.

Contents

1. Introduction

Wind power will undoubtedly play a significant role in the drive toward de-carbonizing global energy systems. Since 2000, worldwide installed wind power capacity has doubled every three years, culminating in aggregate installed capacity (projected to reach 203,500 MW by the end of 2010) which is now capable of satisfying 2% of global electricity consumption [1]. As this paper will detail, the expansion of installed wind power capacity over the past decade can be attributed primarily to rising fossil fuel costs, declining wind power costs and an enhanced propensity of governments to subsidize wind power projects in order to bridge any remaining cost disparities. However, there is still a high degree of "stickiness" associated with wind power development because in many nations, subsidies for supporting wind power project development (or dissuasive measures applied to fossil fuel power generation) are insufficient for closing the cost divide [2,3]. Moreover, even in nations where robust wind power development incentives or fos-

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sil fuel power generation disincentives have rendered wind power projects commercially viable, economic inefficiencies at the project level have tended to stymie development [4–6]. In a nutshell, it can be said that wind power generation costs are approaching parity with costs attributed to conventional, carbon-based sources of energy but the economic advantage still rests with conventional sources.

Amidst this economic backdrop, it should be intuitively obvious that an imperative exists for wind power development proponents to ensure wind power projects are developed in the most economically optimal fashion. For wind power project developers, shaving a few tenths of a cent off of the kilowatts per hour cost of wind generated power can mean the difference between a commercially viable project and a non-starter. For civic authorities who are responsible for implementing municipally funded wind power projects, optimizing the economics of such projects can significantly mitigate the impact of minority opposition groups.

This paper contributes to a better understanding of how to economically optimise wind power projects by consolidating research from the fields of energy economics, wind power engineering, aerodynamics, geography and climate science to identify the key factors which influence the economic optimization of wind power projects. From an applied perspective, the insights on how to minimize costs associated with wind power projects will provide project planners with guidance in regard to the elements they should seek to control when planning wind power projects and provide policy makers with insight into the types of measures that could better foster economically optimized wind power project development. Finally, these insights should also enable policy makers to develop improved economic incentives for stimulating wind power development because a comprehensive understanding of the factors which influence wind power costs provides the knowledge base necessary for establishing more optimal incentivization levels.

The layout of this paper is as follows. Section 2 examines the challenges associated with estimating wind power costs. Sections 3–8 demonstrate how wind system technology, wind quality, site selection, specialised system features, grid connection challenges and climate can influence wind power costs at the project level. Section 9 then looks at the impact that carbon pricing regimes can have on project costs. Section 10 examines indirect costs that are frequently not internalised at the planning stage of wind power projects. Section 11 critically examines the claim that the stochastic nature of wind power flows significantly raises wind power costs. The section also presents viable strategies to minimize the economic impact of intermittent wind flows. Section 12 examines the financial challenges associated with developing wind power projects and recommends solutions for enhancing capitalization of such projects. Section 13 considers the impact of energy market economics on the evolution of wind power over the past decade and speculates on the competitive prospects of wind power in coming decades. Finally, Section 14 presents a short wrap-up.

2. The challenges of estimating the cost of wind power

Table 1 presents a sampling of European wind power cost studies over a five-year period in order to highlight the seemingly capricious nature of wind power generation costs. Looking over these cost estimates, one could not be faulted for concluding that there has apparently been scant progress in reducing wind power costs over this 5-year period, thereby contradicting reports that the cost of wind has progressively declined over the past 30 years and undermining projections by both US Department of Energy and UK government authorities that wind power costs will likely continue to decline over the next 30 years [6,7]. However, such a perception would be specious because the disparate nature of the cost estimates in Table 1 communicate a far more complex truth – wind power generation costs can differ significantly at the project level due to a number of factors that extend beyond choice of technology used.

Table 1
A sampling of wind cost studies.

Characteristics of data	MWh cost (US$)	Base year	References
Wind farm in Denmark	40	2008	[8]
Average cost of onshore wind energy in Sweden	50	2007	[6]
Average cost of wind power	40	2006	[9]
Remote wind system	26	2006	[9]
Onshore wind in general (excluding subsidies)	70	2005	[10]
Large scale onshore systems in general	55	2005	[7]
Onshore wind installations in UK	47	2005	[11]
Offshore wind installations	81	2005	[11]
Large scale wind in general	40–50	2004	[3]

To highlight this point further and bring cost estimates up to date, in 2009, Krohn et al. [12] produced an economic assessment of wind power costs for the European Wind Energy Association that estimated wind power generation costs in Europe ranged between US$87 and US$121 per megawatt hour (MWh) at sites in low quality wind locations,[1] between US$65 and US$87 per MWh at sites characterised by medium quality wind,[2] and between US$54 and US$75 in coastal areas with high quality wind conditions.[3] Although these estimates highlight the importance that wind quality plays in influencing generation costs, the cost ranges associated with each wind quality category also suggest that there are other influences on the cost of wind power that are unrelated to wind quality.

In the sections which follow, key factors which influence the cost of wind power will be examined in order to provide as much insight as possible into the elements which must be managed in order to minimise wind power generation costs associated with a given project.

3. Wind systems and cost

The choice of wind power system has the greatest impact on the cost of wind power generated. Advances in generation technology have fuelled a trend whereby the cost of wind power has declined from US$280 to US$40–70 per MWh over the past 30 years [7]. The rated capacities of wind turbines have increased significantly since the early 1980s. State of the art 20 kW wind turbines of the 1980s now seem like school science projects in comparison to the 6 MW turbines that are being erected today.

The link between wind turbine generation capacity and generation cost stems partly from technical economies of scale. The main components of wind systems are the nacelle components (blade, gears and generator), the tower, the foundation and the balance of plant components (including transformer and transmission cables) [13]. All of these components have declining cost profiles in relation to increased scale. For example, a wind system with twice the generation capacity of another does not require twice the tower height, nor does it require twice the foundation materials or twice the resource inputs for balance of plant components.

[1] Low quality wind sites are defined as sites that generate 1500–1900 full load hours of wind power annually.

[2] Medium quality wind sites are defined as sites that generate 2100–2500 full load hours of wind power annually.

[3] High quality wind sites are defined as sites that generate 2700–2900 full load hours of wind power annually.

However, there are diminishing returns in regard to technical economies of scale. One wind expert contends that in the near future, technical economies of scale may be obviated by amplified increases in the cost of larger wind turbines [6]. Furthermore, energy generated from wind turbines depends on the size of the area swept by the rotor blade. It is believed that the weight of the rotor blade may eventually limit the extent to which the size of the swept area can be expanded [6]. Yet, despite these concerns, technical economies of scale continue to be realized. Advances in turbine technology, lighter component materials, and improvements in wind capture engineering continue to drive down generation costs.

In addition to technical economies of scale, there are production economies of scale that reduce the cost of wind power. Ackerman and Soder [13] estimated that in the 1990s, wind power cost declined by 20% every time the aggregate amount of global installed wind power capacity doubled. One of the negative feedbacks inhibiting future cost reduction stems from amplified manufacturing costs due to elevated steel prices. Nevertheless, DONG Energy [8] provides a forward perspective on the impact of production economies estimating that the cost of wind power can be expected to decrease by 4–10% each time aggregate market capacity doubles.

Although further market growth may indeed catalyze diminishing benefits from technical and production economies of scale, the consensus appears to be that over the next few decades, as the wind power market expands, these economies of scale will place downward pressure on generation costs creating a virtuous circle of continued market growth and further cost decline [6,8,10,13]. Some experts contend that the cost of wind power will fall to approximately US$20 per MWh within the next three decades [9,14]. However, this does not guarantee that a *specific* wind project will generate power at this cost level. The capacity to optimize generation costs depends on a number of other factors that will be examined in subsequent sections.

4. Wind quality and cost

As the Krohn, Morthorst and Awerbuch estimates presented in Section 1 imply, the quality of wind at any given site also has a sizable influence on wind power costs. There are three characteristics of wind quality of particular importance – overall wind speeds, consistency of wind speeds and consistency of wind speed direction. First, absolute wind speed affects rotor speed; therefore, wind speed dictates the optimal size of wind turbines that can be employed. As a rule of thumb, a 10% increase in wind speed can produce a 30% increase in energy production [15]. This is because "*the power of the wind is proportional to the cube of the wind speed*" [6]. Second, actual wind speeds often deviate significantly from the mean. During some periods there may not be enough wind to generate power. At other times, wind speeds may be too high, necessitating turbine lock down. Wind variances occur annually, seasonally, daily, diurnally (day versus night), hourly or even by the second [13]. Consequently, feasibility studies based on "average" wind speeds in a given area (for example see Ref. [16]) should be supplemented by studies investigating wind speed fluctuations. Third, consistency in terms of wind direction can also impact the amount of wind power generated. Although most modern wind turbine systems have a yaw motor which aligns the nacelle to maximize wind collection, the yaw motor is typically set to respond to prolonged directional changes, not to sudden directional fluctuations [6].

These insights convey an important lesson. Whether evaluating the feasibility of individual wind power projects or assessing sites for wind energy potential, estimates based on "average wind speeds" are inadequate. Reliable wind speed estimates should be based on comprehensive temporal analysis of wind patterns (yearly, seasonally, daily, diurnally and hourly) that incorporate data on both wind speed fluctuations and directional variances of wind gusts.

Since wind speed data comes from past observations, even accurate data will not accurately predict future wind patterns. An error margin should always be built into wind quality estimates prior to preparing a financial assessment regarding the viability of a given site. The caveat for any person making decisions based on such estimates is to confirm whether or not an error margin has been built into the calculations; and if so, how much of a margin has been included. One wind expert recommends an error margin of 10% is appropriate [6].

5. Location and cost

Given the importance of wind speed for wind power generation, it should come as no surprise that offshore wind energy is viewed with significant promise. Offshore winds are usually of higher quality. Unfortunately, constructing offshore wind farms is also more expensive.

The present consensus appears to be that although there may be some offshore sites where the additional power generated offsets higher construction costs [6], offshore wind energy is still more expensive than onshore wind energy on a kWh basis [8,17]. In 2005, the British Wind Energy Association [11] estimated that the cost differential was US4.7¢ per kWh for onshore wind power and US8.1¢ per kWh for offshore wind power. By 2009, a study conducted for the European Wind Energy Association concluded that offshore wind power cost on average 50% more than the average onshore site [18], the gap was closing. With offshore technologies improving faster than the more mature onshore technologies, offshore wind power costs are declining faster than onshore costs; therefore, many analysts predict that offshore wind power exhibits highest growth potential [8,18]. As offshore costs approach parity with onshore costs, offshore options may become comparably attractive because offshore sites do not have to contend with as many competing land uses.

6. Specialised system features and cost

Over the past 30 years, a diverse array of system innovations have emerged to improve performance under varied conditions [15]. For example, many nacelles now house a small motor which automatically adjusts the pitch of the blades in response to wind speed variance [19]. In a location which is characterized by inconsistent winds, adjustable rotor blades will, ceteris paribus, improve power output and generation consistency and enhance system profits [13]. As another example, higher towers make it possible for turbines to capture wind which is less affected by ground friction, thereby providing a more consistent source of wind power [6]. Similarly, strategic choices made in regard to transmission infrastructure (i.e. buried underground versus erecting transmission cable towers) can significantly reduce the cost of wind power [20].

Although specific advice concerning how to technically minimize project costs is beyond the scope of this paper, the lesson to extract from the examples put forth is that each decision made in regard to wind power systems has cost implications. Therefore, for policymakers who are commissioning wind power projects through public funds, forcing developers to formally justify the technical choices they have made in preparing a project proposal will enhance cost control.

7. Grid connection and costs

Inauspiciously, wind farms are often established in remote areas to take advantage of land availability and obviate social opposition

[9]. The distance from the site to the electricity grid influences connection costs in two ways. Firstly, spatial separation from power grids means that longer transmission networks and access roads need to be built. This can add as much as US$80 per meter to the cost of a wind power project [6].

Secondly, energy dissipates as it travels along transmission lines. Power leakage increases as distance to the electricity grid increases. Although policymakers are frequently aware of the hard costs that arise due to distance from electricity grids, the phenomenon of leakage is less widely understood. It has been estimated that leakage can be as high as 10% of energy produced [6]. Two factors have the most influence on leakage – distance and the type of electricity conduit used – and management of these two factors will allow engineers to minimize leakage [21].

One other grid connection factor that influences generation cost is the voltage capacity of power lines installed to carry power to the grid. The voltage capacity limits the amount of power that can be delivered to the grid [6]. Consequently, power line capacity can constrain the size of wind farms or necessitate investment in substations to regulate voltage.

8. Climate and wind energy costs

Adverse climates frequently inflate maintenance costs. Consider, for example, wind turbines erected in marine environments. Component parts that are made of steel are prone to corrosion in such environments and must be replaced more frequently. Although less corrosive materials can be substituted for some of the steel parts, substitute materials frequently cost more.

Adverse climates can also affect power production. For example, ice on wind turbine blades jeopardizes system operation. Ice can snap rotor blades and bend rotor drive shafts [13]. Even a light coating of ice on rotor blades can adversely affect aerodynamic properties. There is also a safety risk associated with ice detaching from spinning rotor blades. Historically, in icy conditions, wind turbines were shut down. Consequently, wind farms in colder climates had fewer productive days. Nowadays, wind turbines erected in cold climates can sport blade de-icing features. Nevertheless, even with blade de-icers, turbines frequently need to be shut down (albeit for shorter periods) to clear the ice off the blades [6].

Projects in regions that experience extreme temperatures or extreme wind speeds can also exhibit amplified cost profiles. For example, siting wind turbines in regions that experience prolonged periods with temperatures below $-20\,^{\circ}\mathrm{C}$ can be problematic because lubrication oils become more viscous and steel becomes more brittle. Costly, specialized heaters may be required to minimize problems associated with extreme cold. Conversely, turbines that are installed in regions characterised by extreme heat may require costly cooling systems. Costs may also be higher at sites which are prone to extreme wind episodes such as typhoons or hurricanes because specialized wind systems are required [6].

There are two policy-relevant lessons stemming from research into climatic influence on wind power system performance. Firstly, government authorities who are overseeing public wind farm developments should ensure that project bids specifically address climatic requirements. Secondly, as the example concerning ice on the rotor blades implied, there may be a need for policymakers to develop safety standards for wind power projects.

9. Carbon credits and wind energy costs

One macro influence which significantly influences the cost of wind power is the availability and quantity of carbon credits attached to a given project. For example, under the Kyoto Protocol's Clean Development Mechanism, wind project developers can claim certified emission reduction (CER) credits for the CO_2 that is offset by a given wind project [22]. If a wind energy project offsets emissions from a CO_2 intensive technology such as coal-fired power, carbon credits amounting to as much as US$20 per MWh can be secured over a 15-year period [8]. The European Union's Emission Trading Scheme (EU-ETS) offers similar carbon credit acquisition opportunities for wind project developers.

A caveat for policymakers in regard to carbon credit management is to ascertain the availability of carbon credits prior to initiating discussions with project developers. In this way, responsibility for managing the carbon credit acquisition process and ownership over the credits can be explicated in offers to tender. This injects a degree of financial certainty into a given project and ensures that misunderstandings over ownership of these credits do not arise [14].

10. Indirect wind energy costs and savings

Any cost–benefit analysis related to the siting of a wind power development in a given community should attempt to assess the overall financial impact that the development will have on the community. Research indicates that one source of opposition to wind power stems from concerns over perceptions of adverse economic impact that the development might have on property values and in some cases, tourism revenue [23]. Financial impact assessments can be approximated using hedonic pricing which is an environmental impact estimation technique that uses experience in one community to estimate impact in another community [24]. The scant research that does exist in regard to estimating the impact of wind power projects on property prices and tourism indicates that any adverse impact that does exist is likely short lived [23,25]. In perhaps the most comprehensive analysis on the influence of wind power sites on property prices, Hoen and colleagues at the Berkeley National Laboratory recently analyzed the sale of nearly 7500 single-family homes located within 10 miles of 24 wind facilities in nine U.S. states and found no evidence that the presence of wind power facilities adversely influenced property prices. Furthermore, research in Japan indicates that wind turbines can actually be a boon to tourism in some cases [26]. However, the limited amount of research in this area suggests that formal financial impact studies might be warranted in communities that exhibit sensitivities to this issue. In particular there is a dearth of knowledge regarding how wind power developments influence high value property prices.

If indirect costs associated with a wind energy project (such as the impact on property prices) merit estimation, indirect savings associated with the same project should also merit assessment. In fossil fuel dominant societies, electricity generated by wind turbines would otherwise likely come from fossil fuel power sources which impose both health and environmental costs on communities. High concentrations of sulphur dioxide associated with coal combustion have been linked to the degradation of buildings and monuments as well as to the acidification of lakes and waterways [27]. CO_2 from fossil fuel combustion is also the main anthropocentric contributor to global warming [28]. Furthermore, pollution from coal-fired power plants has been linked to respiratory diseases. To put the health risks into perspective, the Ontario Medical Association estimated that health problems in the late 1990s stemming from pollution attributed primarily to fossil fuel-fired power generation cost Ontario nearly US$1 billion in health costs each year and contributed to over 1900 pre-mature deaths [29].

Although the obviation of pollution-induced health costs can be estimated by accessing scientific studies, estimating the savings from mitigating environmental damage caused by fossil fuel combustion can be a complicated and contentious exercise. There are a number of economic techniques for estimating macro environmental impacts (or in this case, economic costs avoided) such

as hedonic pricing (using real estate valuation techniques), contingent value (assessing societal willingness to pay for a given environmental outcome), replacement cost estimates (useful for man-made structures), dose–response estimates (useful for mediation of waterways) and opportunity cost valuation techniques [24]. Although most environmental economists would be quick to point out that all environmental valuation methods suffer from method-specific weaknesses, making the effort to assign some value to environmental degradation is arguably better than not making the effort at all [30]. An evaluation of these methods transcends the scope of this paper; therefore, interested readers are directed to environmental economics texts [31,32].

Currently, the norm appears to be to avoid integrating societal and environmental costs (and benefits) in energy analysis [33]. Unfortunately, continuing to ignore societal and environmental costs (and benefits) cloaks the true cost of fossil fuel power [34]. Overall, there is widespread consensus that if societal and environmental costs were added to the operational costs associated with fossil fuel technologies, these technologies would not be able to compete economically with wind power technology [12,33,35–37].

11. The added cost of stochastic flows

Even in the most flexible of supply circumstances, electricity load management is complicated by demand-side variances. Demand for electricity varies by season, by week, by time of day and even by the second. An electricity supply system must be able to respond promptly to all these demand variations [6]. The stochastic nature of wind further complicates load management due to supply-side fluctuations because the amount of energy generated from a wind turbine can also vary significantly by year, month, week, day hour and minute [38].

Technically, there are two approaches to stabilize wind generated electricity supply and both pose costs that increase the cost of electricity generated. The first approach is to store wind energy that has been generated but not yet utilized. Prominent storage options include advanced battery storage, pumped hydro, and compressed air energy storage [39]. Compressed air energy storage systems are the most versatile of the current storage technologies; however, the systems are expensive to construct, require fuel to drive the compressor and “leak” energy (only a fraction of the energy gets stored) [39]. In short, although storage is a feasible solution, it adds to the cost of electricity generated.

The other technical approach is to add generation capacity of peak-load support systems such as hydropower or natural gas-fired power. Enhancing capacity of highly responsive electricity generation technologies allows load engineers to compensate for fluctuations in wind power by adjusting the output of the reserve generators. The obvious downside to this solution is that it costs money to purchase back-up systems and the investment is not fully exploited due to the downtime (and combustion inefficiencies) that characterize reserve generators [38].

Although the cost of adding storage or reserve back-up is frequently raised by wind critics as a deterrent to over-reliance on wind power, such cost concerns are exaggerated. A report by the Australia Institute contends that adding approximately 5% wind power to the existing grid would only cost the average household US$15–25 per year extra [40]. Another study, indicates that the additional cost of backup generation (i.e. gas-fired generators) necessary to allow wind power to reach high contribution levels (i.e. 40%) in Australia would increase the cost of wind power by only about 25% [41]. This amounts to a surcharge of approximately US$10–20 per MWh.

Moreover, insinuations that high levels of input from wind power will unfailingly destabilize electricity grids are largely exaggerated. Research indicates that strategic site planning, geographic dispersal of wind power facilities and technical decisions made when selecting turbines (i.e. adjustable rotors, variable speed gearboxes, computerized yaw controls, etc.) can significantly attenuate wind power fluctuations [19,42]. Furthermore, many studies have found that spare capacity already embedded in the average electricity grid is capable to accommodating significant amounts of wind power before further back-up is required [15,41,43,44].

Currently, the consensus appears to be that depending on the electricity grid base-load profile, 10–40% wind energy can be integrated into an electricity grid without having to add storage or additional spare capacity. For grids that are dominated by coal-fired power stations, a 10–20% contribution from wind power represents the norm beyond which additional storage or capacity additions become necessary [3,39,45]. For grids that are dominated by hydropower, a 30–40% contribution from wind power may be achievable [42,46]. There are already examples of nations which rely on wind energy for up to 40% of total electricity demand [47]. Denmark has set a goal of producing 50% of its electrical power through wind energy by 2030 [6]. In fact, some studies go as far as to conclude that even in systems dominated by inflexible base-load energy sources such as nuclear power, the potential contribution of wind energy (without incurring additional storage or reserve capacity) may reach as high as 50% in coming decades through better dispersion of wind resources, improved generation technologies [13] and new energy storage technologies [9,39]. However, it remains to be seen whether or not a system that is supported by such high levels of wind energy is resilient enough to survive the loss the largest generation unit [43].

The relevant insight for policymakers is that the intermittent property of wind can indeed pose logistical problems for managing regional electricity grids but not at the current levels that exist in most countries. At low levels of wind power integration (i.e. 5–10%) existing generation capacity may be able to support additional wind power contribution without any additional costs. At higher levels (i.e. 20%+) adding spare capacity or energy storage systems will increase the cost of wind power, but only moderately.

12. Front-end costs

There has been criticism that high front-end capital costs associated with wind energy projects deter the pace of wind power capacity expansion [17]. Initial capital costs are estimated to account for approximately 70–80% of the total cost of wind energy [8,48]. However, such criticism fails to recognise the strategic advantage to a front-end heavy capital profile – reduced operational risk. Once the front-end investment has been committed, further costs are negligible. Wind power operating and maintenance costs are estimated at approximately US$12–20 per MWh [8,12]. Contrast this to the investment scenario faced by fossil fuel power plant developers. The front-end investment for fossil fuel plants may be slightly lower compared to wind power facilities of similar output capacity; however, the highest cost element (the fossil fuel resource) is still prone to inflationary forces. Nevertheless, the perception that capital costs may deter investment in wind power implies that guaranteeing capital loans supported by claims on future revenue flows may be a viable policy tool to help wind power developers raise the capital necessary to accelerate the pace of wind power development.

13. The influence of competitive technologies on wind power cost

The evolution of wind power generation costs over the past decade cannot, and indeed should not, be considered in isolation

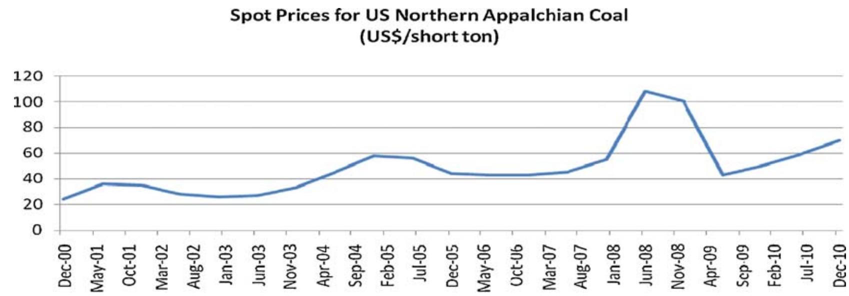


Fig. 1. An indication of coal spot price trends.
Source: US Energy Information Administration (US Energy Information Administration web-site: http://www.eia.doe.gov/coal/page/coalnews/coalmar.html. This data is based on the market prices for one short ton of Northern Appalachian coal (13,000 Btu; less than 3.0 lbs SO_2 per mmBtu).

from the dynamics of the electricity generation market. In particular, what has transpired in global coal markets has played an enormous role in the evolution of wind power because for most economies, coal is the dominant source of electricity generation and consequently, represents the economic market standard against which wind power developers must try and compete. Therefore, any assessment of the economic prospects of wind power would not be complete without understanding the economic context within which wind power competes. This section examines coal price trends over the last decade and speculates on future coal prices levels and what this may portend for wind power development.

As Fig. 1 illustrates, between December 2000 and December 2004, the spot price for US Northern Appalachian coal (which serves as a proxy for describing aggregate coal pricing trends) remained within a fairly stable trading range of US$25–35 per short ton. During this period, worldwide installed wind power capacity (Fig. 2) expanded in a relatively phlegmatic fashion (given climate change concerns) with annual growth escalating from 6859 MW added in 2002 to 11,331 MW added in 2005.

One interpretation of this moderate pace of wind power capacity expansions during this period is that the low, relatively stable cost of coal provided little incentive for utilities to alter energy mixes. In terms of wind power development, such moderate growth tended to inhibit the realization of economies of scale which would otherwise have enhanced the decline of wind power costs. In short, it can be said that improvements in wind power cost during this period were driven primary by technical improvements in wind system technology – larger turbines, more effective rotor blade designs, and improvements to gearboxes and generators – as well as by more effective site planning [6,8,15].

In December 2004, the spot price for US Northern Appalachian coal spiked to nearly US$60, double its traditional trading range (Fig. 1). This sent shock waves through the global utility sector and one of the repercussions was increased interest in alternative energy technologies. Accordingly, 2006 saw over 15,000 MW of wind power capacity installed – nearly double the growth rate of the previous three years – and in 2007, as coal prices hovered in the US$40–50 range, another 19,808 MW of wind power generation capacity was added worldwide.

The 2004 spike in the price of coal benefited the wind power industry in two ways. First, the instability surrounding coal futures narrowed the cost gap between coal-fired power and wind power and raised the risk of continued reliance on coal as a dominant source of electricity production. Second, the sudden escalation in demand for wind turbines enabled unprecedented economies of scale. It can perhaps be argued that this was the first period in the history of the wind power industry that economic savings from scale actually surpassed the economies realized technological improvements. By the end of 2007, wind power had significantly closed the economic gap with coal-fired power; however, the gap that remained was still significant enough to stifle broad scale investment in wind power.

In the summer of 2008, the spot price of high grade US Northern Appalachian Coal began a renewed ascent which culminated in a spot price of US$150 per short ton in September 2008. Although, the cost retreated to approximately US$60 per ton in response to the autumn 2008 global economic slowdown which quashed demand for coal, the cost (US$69.50 per short ton as of November 4, 2010) has remained significantly above historic levels.[4] As Fig. 2 further illustrates, this new phase of coal market instability has further emboldened investment in wind power. More added capacity is expected for 2010 (44,287 MW) than existed in worldwide aggregate in 2003 (39,295 MW). Aside from the catalytic boost from global efforts to reduce greenhouse gas (GHG) emissions, one of the main reasons why wind power development is enjoying such a dynamic period of growth is that the elevated cost of coal has now continued for almost six years, and increasingly, utilities are beginning to understand that the days of cheap coal may indeed be over. At the new trading range of between US$50–70 per short ton, the cost divide between wind power and coal-fired power is progressively narrowing. In fact, some researchers have asserted since the start of the escalation of coal prices that wind power is now cheaper than coal-fired or nuclear-powered energy under certain circumstances [35]; though absolute assertions of this kind are hard to defend unless full environmental costing were included in the calculation [36].

The case for wind power investment is strengthened when upward price pressure on fossil fuel feed-stocks is factored into the equation. The US Energy Information Administration estimates that global coal consumption will increase by 65% between 2006 and 2030 [49]. Many analysts believe that such levels of consumption will dangerously deplete already degraded coal reserves. In a study for the European Commission, Kavalov and Peteves [50] provide a succinct overview of trends in the coal industry:

- (Due mostly to accelerated consumption), from 2000 to 2005, the world's proven reserves-to-production ratio of coal in fact (declined) from 277 to 155 years.
- Coal production costs are steadily rising all over the world due to the need to develop new fields, increasingly difficult geological conditions and additional infrastructure costs associated with the exploitation of new fields.
- The USA and China – former large net exporters – are gradually turning into large net importers with an enormous potential demand, together with India.

[4] US Energy Information Administration web-site: http://www.eia.doe.gov/coal/page/coalnews/coalmar.html.

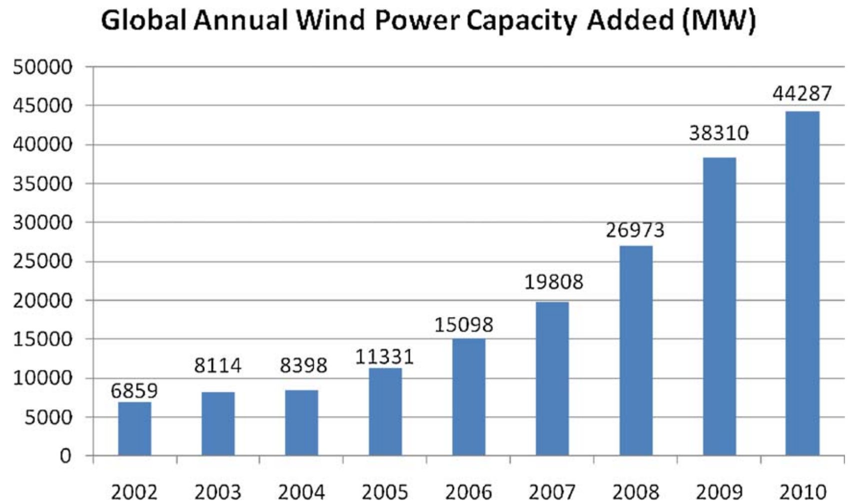


Fig. 2. Annual amount of wind power capacity added.

Source: World Wind Energy Association [1].

• These trends suggest a likely significant increase of world coal prices in the coming decades.

These observations suggest that over the coming decades the economics of energy generation may shift in favour of wind power. If such an occurrence materializes, the need for managing all the influences affecting wind power costs in order to improve the competitiveness of wind power projects will likely be supplanted by the desire to manage all the influences affecting wind power costs in order to minimize energy costs to the consumer. The point being, in either case, the need to manage the elements influencing wind power generation costs will be relevant regardless of whether or not wind power supersedes coal as the economically preferred source of electricity generation.

14. Conclusion

This paper has conveyed some insights into why successful private wind power project developers make the decisions they do regarding site selection and choice of wind power systems; however, all too often these cost optimising elements are ignored by less-seasoned project developers, resulting in economically sub-optimal projects. For public officials who are leading publically funded initiatives to expand wind power capacity, these insights can be referenced to guide the development of economically optimised wind power projects. Moreover, for policymakers who aspire to level the competitive playing field by developing and implementing policy instruments to de-carbonize regional electricity mix profiles, the two sections which examined "carbon credits" and "indirect wind energy costs and savings" highlight important issues to be addressed when designing policy instruments to influence market behaviour. Finally, it is worth re-iterating the observation that concern over the stochastic nature of wind power is over-exaggerated at low levels of wind power contribution. Putting all these insights together, one should be left with an understanding that well-planned wind power projects carried out in conjunction with policies designed to internalise all external costs cultivates the necessary conditions for wind power project developments that are economically benign additions to the electricity mix. In this evolutionary era of energy, where there are pressures to decarbonize energy systems and wind power represents a technology that is nearly able to compete on a level playing field with conventional fossil fuel technologies, the difference between economic success and failure often rests with smart decisions made at the project level in the areas identified in this paper.

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